

Deliverable Number D11.3: Guidelines for long-term monitoring; WP11; lead beneficiary no 3 (NIVA)

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 265847.

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Summary

ECO₂ conducted a comprehensive offshore field programme at the Norwegian storage sites Sleipner and Snøhvit and at several natural CO₂ seepage sites in order to identify potential pathways for CO₂ leakage through the overburden, monitor seep sites at the seabed, track and trace the spread of CO₂ in ambient bottom waters, and study the response of benthic biota to CO₂. Based on its extensive field programme ECO₂ developed guidelines for the monitoring of sub-seabed storage sites. ECO₂ recommends that overburden, seabed, and water column should be surveyed applying the following techniques: i) 3-D seismic imaging of seals and overburden, ii) high-resolution bathymetry/backscatter mapping of the seabed, iii) hydro-acoustic imaging of shallow gas accumulations in the seabed and gas bubbles ascending into the water column, iv) video/photo imaging of biota at the seabed, v) chemical detection of dissolved CO₂ and related parameters in ambient bottom waters. Additional targeted studies have to be conducted if active formation water seeps, gas seeps, and pockmarks with deep roots reaching into the storage formation occur at the seabed. These sites have to be revisited on a regular basis to determine emission rates of gases and fluids and exclude that seepage is invigorated and pockmarks are re-activated by the storage operation. Baseline studies serve to determine the natural variability against which the response of the storage complex to the storage operation has to be evaluated. All measurements being part of the monitoring program, thus, need to be performed during the baseline study prior to the onset of the storage operation to assess the spatial and temporal variability of leakage-related structures, parameters, and processes.

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1. Introduction

Carbon Capture and Storage (CCS) is a technology for the reduction of CO₂ emissions from power plants and other sources at the European and international level. The EU is supporting many R&D activities in this field. The ECO₂ project derives from the FP7-OCEAN-2010 call. It started in 2011 and lasted until May, 2015. The project had 27 partners and was managed by GEOMAR, Germany. The project addressed the risks associated with the storage of CO₂ below the seabed, particularly about the short-term and long-term impacts of CO₂ storage on marine ecosystems.

This report is based on the outcomes of several workshops held under the auspices of the ECO₂ project at which all current aspects of marine CCS monitoring were discussed and appraised. The project had the leading European researchers in technologies for many aspects of marine (including near-surface benthos) monitoring, which is the core of this report. Scientists (biologists, ecologists, oceanographers, geologists, marine chemists, engineers), legal experts, socio-economists and industry representatives participated in these discussions to develop guidelines for monitoring. The role of WP 11 (CCT1) was to provide a focus for the synthesis and integration of knowledge towards the optimization of monitoring methods for different scenarios of leakage. To fulfil this role WP11 hosted 3 workshops, these constitute the three Tasks and the first two Deliverables of the WP 11. Deliverable 11.3 is the last deliverable of the WP, a report on guidelines for long-term monitoring guidelines relevant for both existing and proposed CO₂ storage sites. The scope of the present Deliverable is to synthesise all of the knowledge on monitoring technologies and strategies gained during the ECO₂ project period. A best practice guide for the management of sub-seabed CO₂ storage sites was developed by WP14, the present Deliverable material is part of the guide.

ECO₂ conducted a comprehensive field programme at two operating CO₂ geological storage sites and at several natural CO₂ seeps in order to identify potential pathways for CO₂ leakage, locate seep sites at the seabed, track and trace the spread of CO₂ in ambient bottom waters, and study the response of benthic biota to CO₂. The following

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recommendations are based on these field studies and the related lab and modelling work. They concern the shallow part of the storage complex, i.e. seals, sedimentary overburden, seabed, bottom waters covering the seabed, and benthic biota settling at the seabed. We aim to define how operators should characterize this system in a ***baseline study prior to the operational phase*** and how ***monitoring*** should be performed ***during the operation***. We recommend that the same techniques and approaches should be applied in both phases since baseline studies serve to characterize the natural variability against which monitoring data are evaluated to detect anomalies related to the storage operation. In the following section, we suppose that storage formations are characterized in detail during site selection and that numerical modelling is performed to forecast the spread of CO₂ in the reservoir and describe the future shape and maximum size of the subsurface CO₂ plume after site closure. The extent of the seabed area and the size of the sub-seafloor volume that need to be characterized and monitored will be delineated by these modelling studies.

2. Monitoring

CO₂ leakage can occur only if fractures, seismic pipes and chimneys, or abandoned wells cutting through seals and overburden have higher permeability than the background sealing formations. Upward migration of CO₂ via large-scale vertical structures can be imaged by seismic data while leakage through wells and other narrow structures is not detectable by geophysical surveys. Additional measurements need to be conducted at the seabed to detect CO₂ release through these small-scale features. Early precursor signs of potential CO₂ leakage at the seabed are the release of formation waters and natural gas filling the subsurface plumbing system which are pushed towards the surface by rising, buoyant CO₂. Depending on water depth and bottom water temperature, CO₂ will be subsequently emitted either as gas bubble or as liquid droplet. CO₂ also dissolves during its passage through water-filled high-permeability conduits and may be emitted in dissolved form together with expelled formation fluids. Monitoring at the seabed should thus be able to detect seeping formation water, natural gas, dissolved CO₂, CO₂ gas bubbles and, at water

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depth larger than ca. 300 m, liquid CO₂ droplets. Special care has to be taken to monitor active and dormant natural seepage sites identified during site selection and baseline surveys since fluids and gases migrating through the overburden will tend to use their roots as conduits and leave the seabed through these already existing outlets.

Monitoring activities can be separated in surveys covering the entire storage complex and targeted studies focused on seeps, abandoned wells, and other specific sites at the seabed. The following **surveys** should be conducted repeatedly over the life time of a storage site:

- **3-D seismic** surveys to detect/exclude CO₂ ascent via large-scale features cutting through seals and overburden (fractures, seismic chimneys and pipes). Operators will conduct and repeat 3-D seismic surveys to image the spread of CO₂ in the storage formation. It is, however, important to record and evaluate data not only from the storage reservoir but also from the overlying sequences to detect/exclude changes in seismic signatures indicating upward migration of CO₂, natural gas, and formation fluids through seals and overburden.
- **Bathymetry/backscatter** surveys to identify and locate formation water seeps at the seabed. Formation water seepage creates seabed structures with distinct morphologies and specific acoustic backscatter properties. A good example is the Hugin Fracture which was discovered in the Central North Sea applying high-resolution backscatter imaging (Fig. 1).
- **Hydro-acoustic** surveys of shallow subsurface and water column to detect and locate subsurface shallow gas accumulations and gas bubble seeps at the seabed. These surveys serve to detect any signs of invigorated gas seepage activity. Sub-bottom profiler and multi-beam echo-sounder systems providing suitable spatial coverage and resolution are commercially available. They can visualize shallow gas accumulations and gas bubbles ascending through the water column (Fig. 2).
- **Video/photo** surveys to observe biological indicators for formation water and gas seepage. Mats of sulphide-oxidizing bacteria are often found at seep sites where methane-bearing formation waters and gas bubbles emanate from the seabed. These bacterial mats are easily identified on videos and still photos and are useful indicators for seepage (Fig. 3). CO₂ leaking from the storage formation affects animals living in the sediment (benthic

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infauna). They try to escape from the sediment and accumulate at the seabed. Conspicuous clusters of infauna and their remains at the seabed may thus indicate CO₂ leakage (Fig. 4).

- **Chemical** surveys to measure CO₂ concentrations and related parameters in bottom waters above the storage complex. Dissolved CO₂ can be detected in-situ with suitable chemical sensors and in water samples retrieved from the seabed. CO₂ leakage affects the chemical composition of seawater and creates strong chemical anomalies in bottom waters located just a few meters above the seabed (Fig. 5). Additional chemical substances such as dissolved oxygen and nutrients should be included in the monitoring program to better discriminate between natural background CO₂ and CO₂ leaking from the storage formation. The release of reducing formation fluids can be detected by sensors measuring the redox potential (Eh) of ambient bottom waters (Fig. 6).

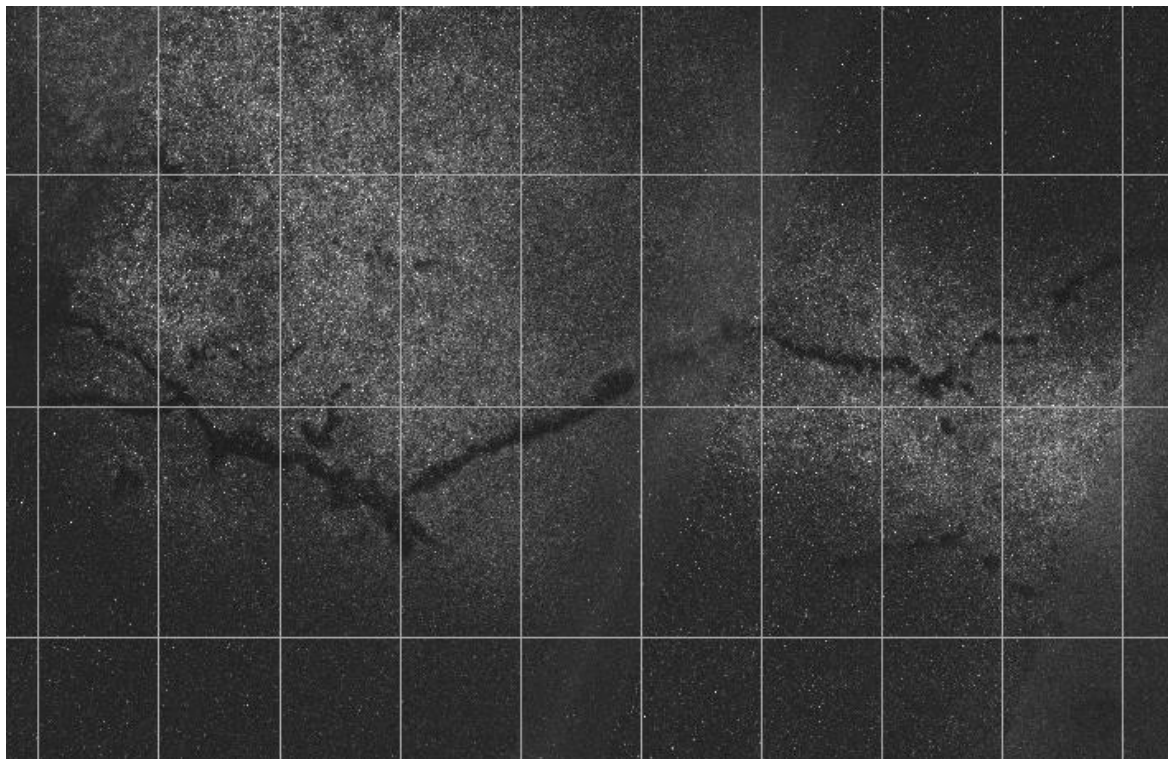


Figure 1: Backscatter image of a section of the Hugin Fracture (dark branching seabed structure) recorded by the HISAS 1030 interferometric SAS system mounted on an AUV. The

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Hugin Fracture is ca. 3 km long and 1-10 m wide and is located in the Central North Sea, 25 km north of the Sleipner storage site (image provided by R. Pedersen, University of Bergen).

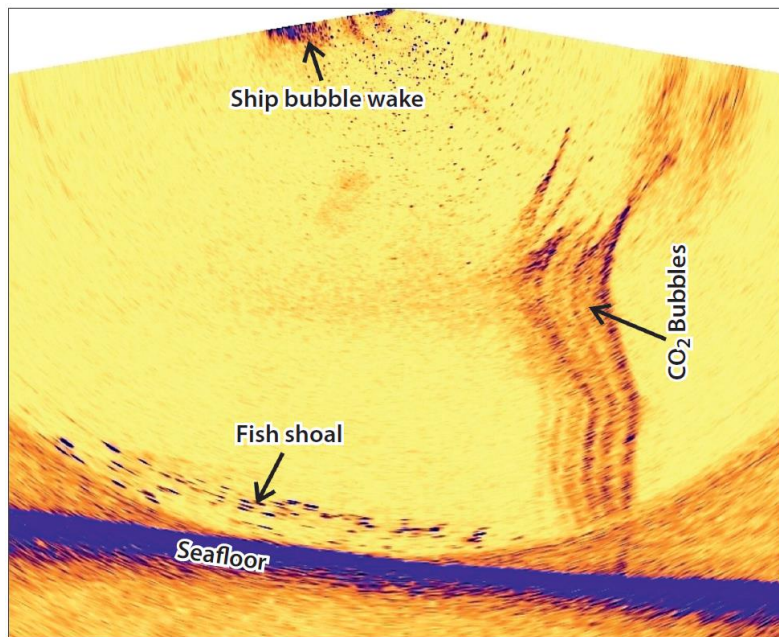


Figure 2: Hydro-acoustic image of CO₂ bubble streams emanating from the seabed at the natural seep site Panarea located in the Mediterranean Sea near Sicily. Data was recorded at 200 kHz using an R2Sonic 2024 installed on RV Urania in 2011 (Schneider von Deimling and Weinrebe, 2014)



Figure 3: White bacterial mats (arrow) at the seabed in the vicinity of an abandoned well in the North Sea. Images recorded using UK HYBIS ROV deployed from UK NERC RRS James Cook in 2012 (image provided by C. Hauton, University of Southampton).

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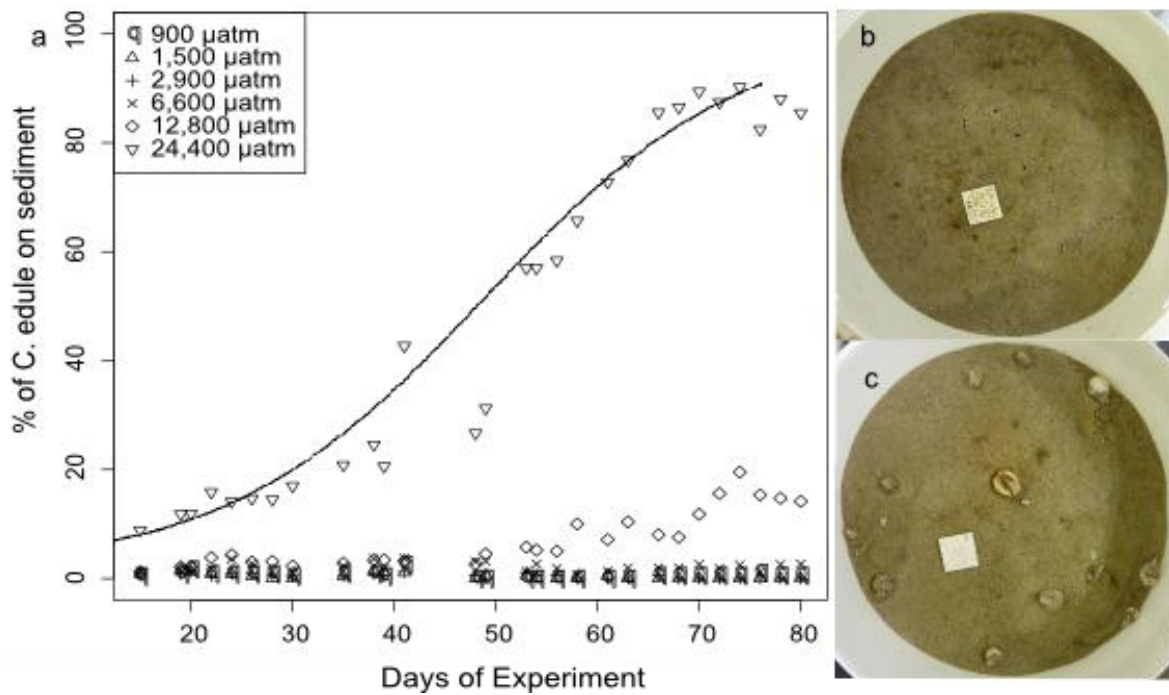


Figure 4: Behavior of the common cockle *Cerastoderma edule* in response to elevated pCO₂. (a) Average abundance (as a percentage of the total) of non-buried cockles in six different treatments over the 80-days experiment. At a concentration of 24,400 µatm over 80% of the cockles were found on the surface of the sediment after 80 days of exposure. (b) Image of the control experimental unit: sediment surface with cockle siphons opened and visible, but no cockles on the sediment surface. (c) At 24,400 µatm cockles have accumulated on the sediment surface at the end of the experiment (data and images provided by F. Melzner, GEOMAR).

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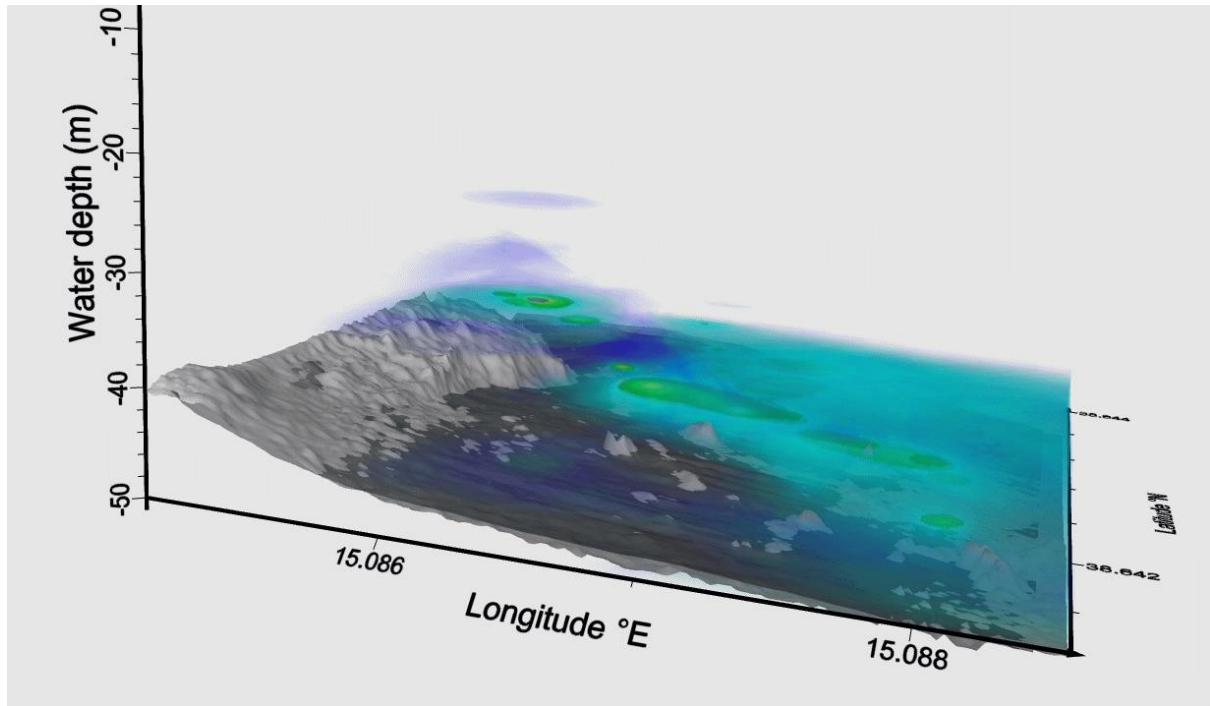


Figure 5: CO₂ plume above the seabed at Panarea (size: 300 x 400 m). Greenish colors indicate dissolved pCO₂ values in the range of 500 – 650 µatm clearly exceeding the local background value of ca. 390 µatm (blue color), resulting in pH values of 0.1-0.35 units below the ambient pH of 8.15. The data were recorded with a chemical sensor (HydroC, CONTROS) which was towed above the seabed with RV Poseidon in May 2014 (Schmidt et al. 2015).

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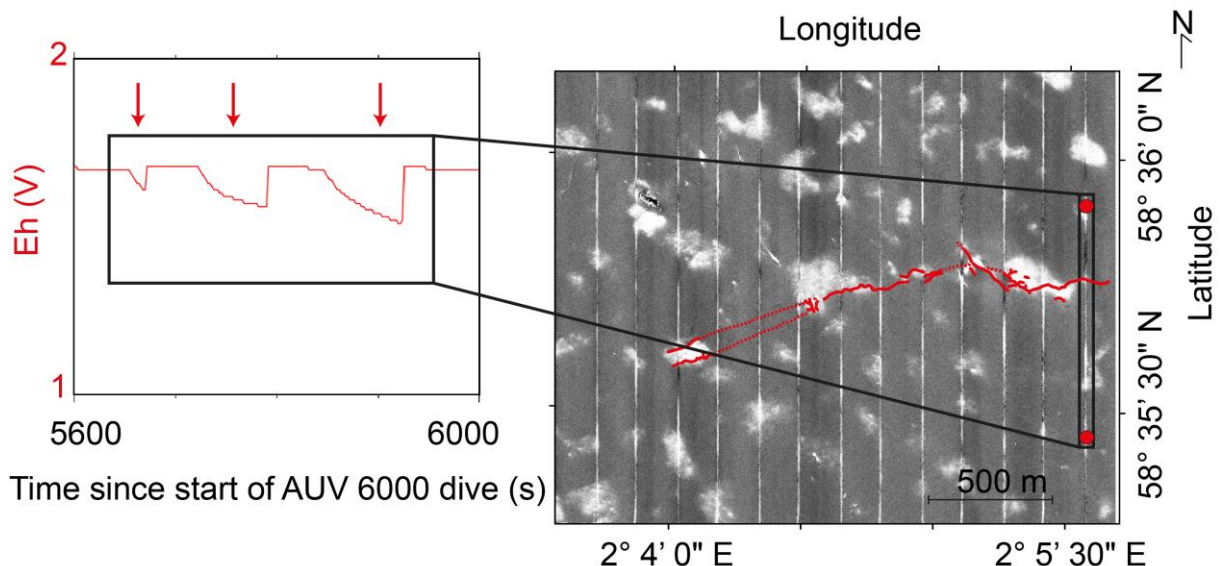


Figure 6: Chemical sensors deployed on NERC AUV Autosub 6000 successfully detected seepage of reduced (low Eh) fluids from the region of the Hugin Fracture. The figure on the right shows a backscatter image of the seafloor, with the position of the Hugin Fracture shown in red. The AUV was flown at a height of 12 m above the seafloor, from the upper red circle to the lower red circle, and data recorded by the Eh sensor are shown on the left. Arrows indicate negative excursions in Eh, as the AUV encountered reduced (low oxygen) fluids. The location of the fracture is shown by the middle arrow (data and images provided by R. James, NOCS).

Surveys can be conducted using autonomous underwater vehicles (AUVs) and/or monitoring vessels. Commercially available AUVs can be equipped with suitable instruments (echo sounders, hydrophones, chemical sensors, still camera, etc.) to conduct multiple surveys with full areal coverage at affordable costs (Fig. 7). Each of the surveys should, however, be conducted at a specific height above the seabed to achieve optimal results.

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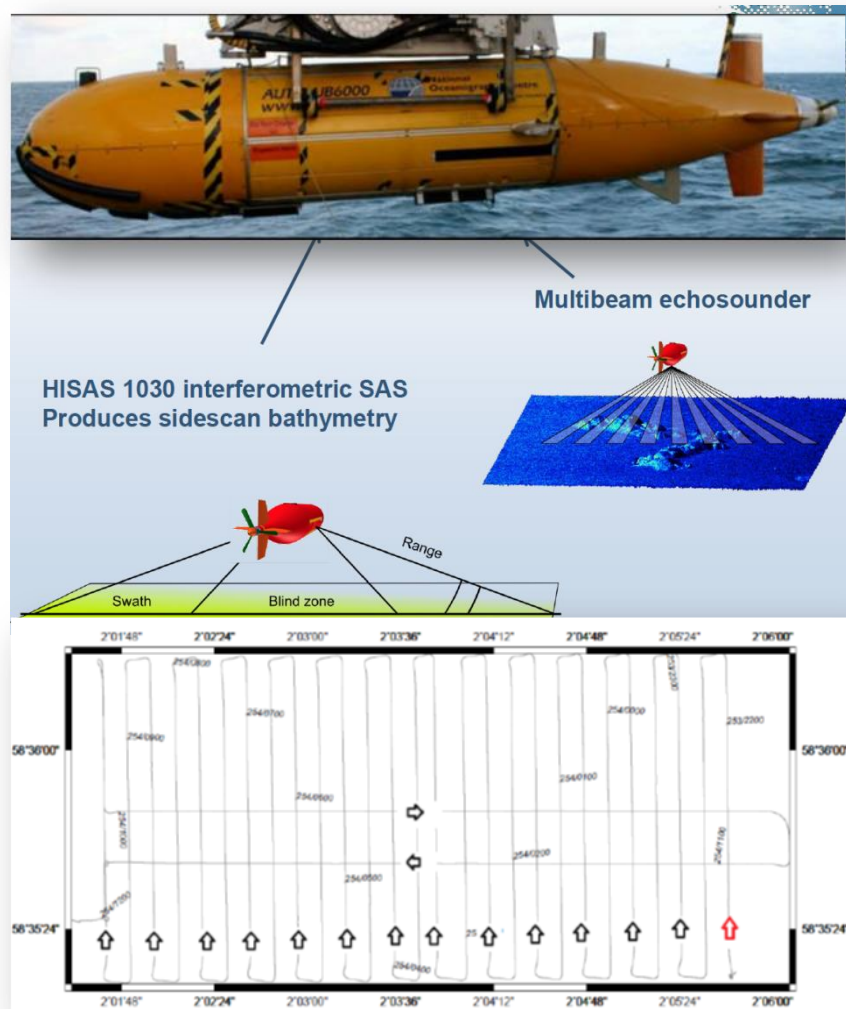


Figure 7: AUV surveys. Platforms such as the NERC AUV Autosub 6000 (top) and the HUGIN AUV (center) have been deployed to map expanses of the North Sea during ECO₂. The navigation track plot (bottom) mapped from Mission 62 of Autosub from the RRS James Cook in 2012 is shown as an example. The track represents 71 km of seabed surveyed at a maximum water depth of 88 m. During the mission >70,000 overlapping still images were recorded. Image analysis can be automated to detect, e.g. shells of dead organisms on the sea bed. Repeating monitoring of the same track could be used to identify changes in the abundance and distribution of shells over time, indicating changes due to fluid leakage through the sediment. AUVs can be equipped with multiple instruments to perform

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bathymetry/backscatter, hydro-acoustic, video/photo, and chemical surveys (images provided by C. Hauton, University of Southampton, and R. Pedersen, University of Bergen).

Additional targeted studies have to be conducted if active formation water seeps, gas seeps, and pockmarks with deep roots reaching into the storage formation occur at the seabed. These sites have to be revisited on a regular basis to determine emission rates of gases and fluids and exclude that seepage is invigorated and pockmarks are re-activated by the storage operation. If new seeps develop during the operational phase, they have to be investigated and sampled in detail to determine the origin and chemical composition of the seeping fluids and gases and their emission rates. These studies have to be conducted with remotely operated vehicles (ROVs) deployed from suitable monitoring vessels. Samples have to be taken for chemical analysis and instruments have to be deployed at the seabed to measure fluxes and emission rates (Fig. 8).



Figure 8: ROV Kiel 6000 is deployed at the seabed to take sediment samples from a bacterial mat patch located within the Hugin Fracture (left). Pore fluids are extracted from the retrieved sediments to determine the chemical composition and origin of formations fluids

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and dissolved gases seeping through the seabed. Subsequently, a benthic chamber lander is placed at the seabed (right) to measure formation water fluxes and determine emission rates (images provided by P. Linke, GEOMAR).

3. Baseline studies

Baseline studies serve to determine the natural variability against which the response of the storage complex to the storage operation has to be evaluated. All surveys being part of the monitoring program, thus, need to be performed more than once during the baseline study prior to the onset of the storage operation. Hence, an appropriate baseline study includes 1) 3-D seismic, 2) bathymetry/backscatter, 3) hydro-acoustic, 4) video/photo, and 5) chemical surveys covering the entire storage complex. Developers of CO₂ storage sites will typically aim to avoid active seep sites, deeply rooted pockmarks and other critical seabed features during site selection. However, this may not always be possible since degassing and dewatering structures are characteristic features of all sedimentary basins. If these sites occur above the storage complex, they need to be investigated in detail during the baseline study. Sediment cores and pore fluids have to be sampled at these sites and at reference stations not affected by fluid and gas flow. The chemical composition of recovered pore fluids has to be analysed to determine the source depths of ascending formation fluids and gases and the chemical signature of near-surface pore fluids at the reference locations and dormant pockmarks prior to the onset of the storage operation. Any changes in chemical composition detected during the monitoring phase would indicate that these near-surface systems are affected by the storage operation with potentially adverse effects on marine ecosystems. Since the release of gases and fluids at active seeps may be amplified by the storage operation, emission rates and their temporal variability have to be assessed prior to the onset of the storage operation. This is a considerable challenge since gas and water fluxes at cold seeps and abandoned wells feature strong temporal variability over a wide range of time scales (hours to years). Continuous time series data recorded over a period of at least one year are thus needed to capture the variability of these systems. Stationary

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lander systems have been applied successfully by academia to record time series data at cold seep sites (e.g. gas flux quantification based on hydro-acoustic bubble detection, fluid flow meters based on osmosis sampling). Some of these systems are now commercially available and should thus be employed during the baseline study at active seeps located above the storage complex.

CO₂ contents of bottom waters are highly dynamic also at storage sites where no seepage occurs. In the North Sea, pCO₂ values are close to atmospheric values during the cold season when the water column is well mixed whereas CO₂ values increase towards the seabed during the warm season when the water column is stratified. This natural CO₂ enrichment is driven by the degradation of marine organic matter producing metabolic CO₂ in the water column and at the seabed. The extent of the enrichment depends on biological activity, current velocities, and local rates of horizontal and vertical mixing. It varies not only between seasons but also from year to year. It is, thus, challenging to fully explore and quantify the natural variability of the near-seabed CO₂ system. To address and minimize this problem, ECO₂ developed and successfully tested a new sensitive tracer (C_{seep}) which highlights the impact of leakage-related CO₂ on bottom water chemistry and largely excludes the effects of metabolic CO₂ (Botnen et al., 2015). It employs the fact that biological production of CO₂ is always associated with a certain amount of oxygen consumption and nutrient release while CO₂ leakage has no specific effect on oxygen and nutrient levels in ambient bottom waters (Fig. 9). Baseline and monitoring surveys should thus aim to measure concentrations of dissolved inorganic carbon, alkalinity, salinity, phosphate and oxygen and apply these data to determine the concentration of the C_{seep} tracer in ambient bottom waters above the storage complex which should cluster at values close to zero prior to the onset of the storage operation. The chemical baseline is also shifted by the uptake of anthropogenic CO₂ via the seawater-atmosphere interface inducing a continuous increase in background CO₂. Additional measurements at reference stations upstream from the storage site can be applied to assess this effect during the operational phase since it affects the ocean at large and not just the storage area.

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Efforts and costs for the recommended baseline and monitoring studies increase in proportion to the number of seep sites situated above the storage complex. The guidelines presented in this document, thus, provide strong financial incentives to avoid these features during site selection as far as possible and may thereby help to minimize the likelihood that CO₂ will leak from sub-seabed storage sites.

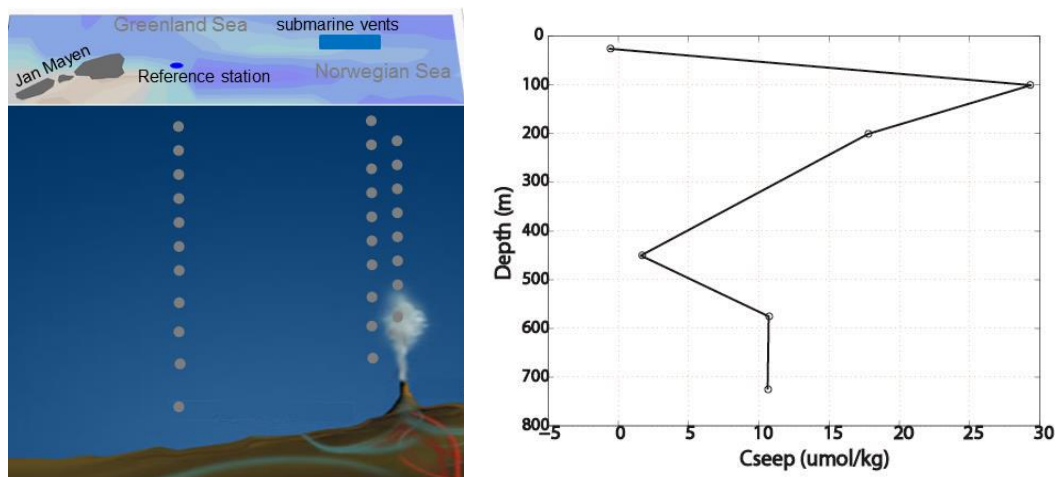


Figure 9: C_{seep} concentrations in bottom waters at a hydrothermal vent field in the Norwegian Sea near the Jan Mayen Island (Botnen et al. 2015). Left panel: 3-dimensional sketch of the location of the hydrothermal vents, the reference station, and sampling depths during the measurement campaign, July-Aug 2012. Right panel: Excess DIC input from subsea hydrothermal vents (in micro-moles of carbon per kg of seawater) determined for various depths in the water column. In contrast to cold seeps, hot vents produce buoyant CO₂ plumes rising towards the surface.

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